Lidar for NASA Applications

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Sensors and Instrumentation Webinar

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LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Outline

- **Introduction to active optical systems, primarily lidars, for NASA applications**
  - **Active optical systems characterized by use of laser source**
- **Example development – water-vapor lidar transmitter**

Active Optical Remote Sensing Technologies

AORS Need: National need exists for reliable, efficient, space-capable AORS systems for civilian and defense applications in the area of Earth sciences, planetary exploration, aviation safety, chemical and biological detection, and tactical imaging. Core technology developments for these applications are not addressed by industry suppliers because of limited market.

Unique AORS Capabilities:

- High resolution profiling capability for atmospheric trace species
- High precision tropospheric wind measurements
- Wavelength specificity for chemical and biological detection
- Altimetry for surface mapping, Ocean mixed layers, ice topography

AORS Applications:

- Weather and severe storm prediction (winds, humidity)
- Atmospheric chemistry, climate and radiation (ozone, aerosols, clouds)
- Carbon cycle (CO_2, biomass)
- Surface mapping (ocean, land, ice)
- Space science (planetary exploration, space transport, communication)
- Chemical and biological agent detection (Homeland Security, DoD)

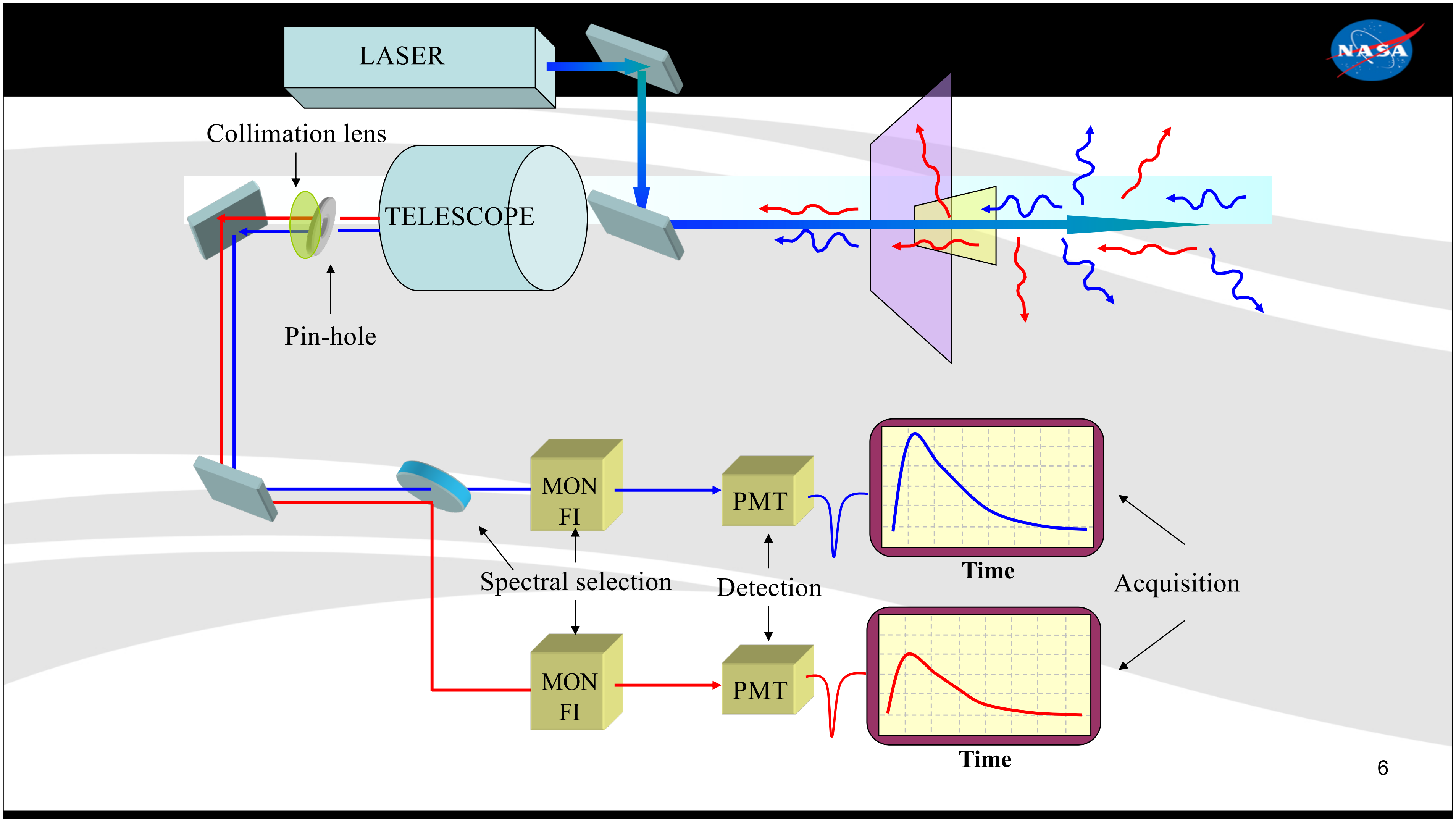
AORS Strategies

- Laser based instruments are applicable to a wide range of NASA's Earth Science, Planetary Science, Aeronautics, and Human Explorations and Operation Mission Directorate needs
- Risk in lidar missions can be significantly reduced by progress in a few key technologies
- Modest NASA investment towards proposed strategy will have significant impact on future space-based active remote sensing missions
- Strategic alliance with other government organizations, industry, and academia for leveraging and accelerating advancement of key technologies

LIDAR - LIght Detection And Ranging

Lidar is analogues to Radar, where lightwaves, instead of radiowaves, are sent into the atmosphere and returns are collected which contains the information about the interacting atmospheric constituents, their microphysical properties and profile.

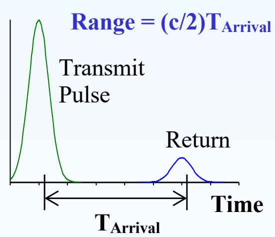
Lidar is an active optical remote sensing technique able to provide measurements with a very high resolution in time and altitude


LASER
Collimation lens
TELESCOPE
Pin-hole
MON
FI
PMT
Time
Spectral selection
Detection
Acquisition
MON
FI
PMT
Time

Lidar Techniques

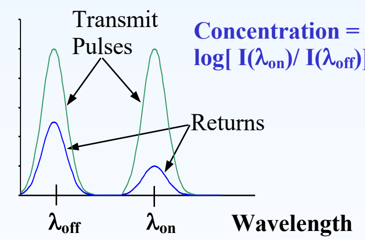
Altimetry Lidar

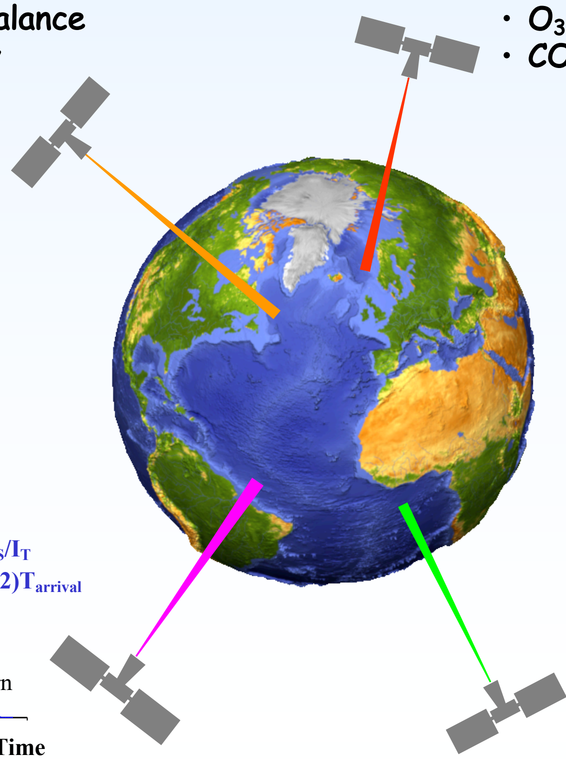
- Ice Sheet Mass Balance
- Vegetation Canopy
- Land Topography



Differential Absorption Lidar (DIAL)

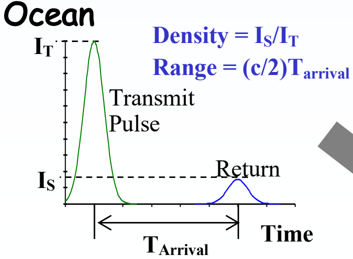
- O_3, H_2O (profile)
- CO_2, CH_4 (column)





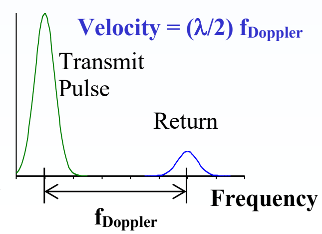
Backscatter Lidar

- Cloud
- Aerosol
- Ocean



Doppler Lidar

- Wind Fields



Active Optical Measurements in the Earth Sciences

Weather

Tropospheric Winds

Atmospheric Temperature and Water Vapor

Cloud Particle Properties

Cloud System Structure

Storm Cell Properties

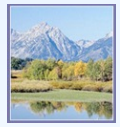
Climate Variability

Ocean Surface Currents

Deep Ocean Circulation

Sea Ice Thickness

Ice Surface Topography

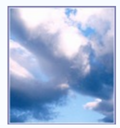


Earth Surface & Interior

Land Surface Topography

Surface Deformation

Terrestrial Reference Frame



Atmospheric Composition

Aerosol Properties

Total Aerosol Amount

Cloud Particle Properties

Cloud System Structure

Ozone Vertical Profile & Total Column Ozone

Surface Gas Concentrates

Water & Energy Cycle

Atmospheric Water Vapor

River Stage Height

Carbon Cycle & Ecosystems

Biomass

Vegetation Canopy

Fuel Quality & Quantity

CO_2 & Methane

Trace Gas Sources

Land Cover & Use

Terrestrial & Marine Productivity

Doppler

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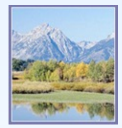

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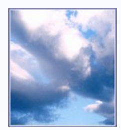

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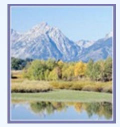

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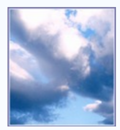

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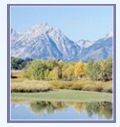

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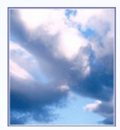

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Backscatter

LIDAR is a Multi-Enterprise Need

NASA Enterprises Needs

LIDAR

Science

- *Clouds/Aerosols*
- *Tropospheric Winds*
- *Ozone*
- *Carbon Dioxide*
- *Biomass Burning*
- *Water Vapor*
- *Surface Mapping*
- *Laser Altimetry*
- *Oceanography*
- *Surface Topography*
- *Molecular Species*

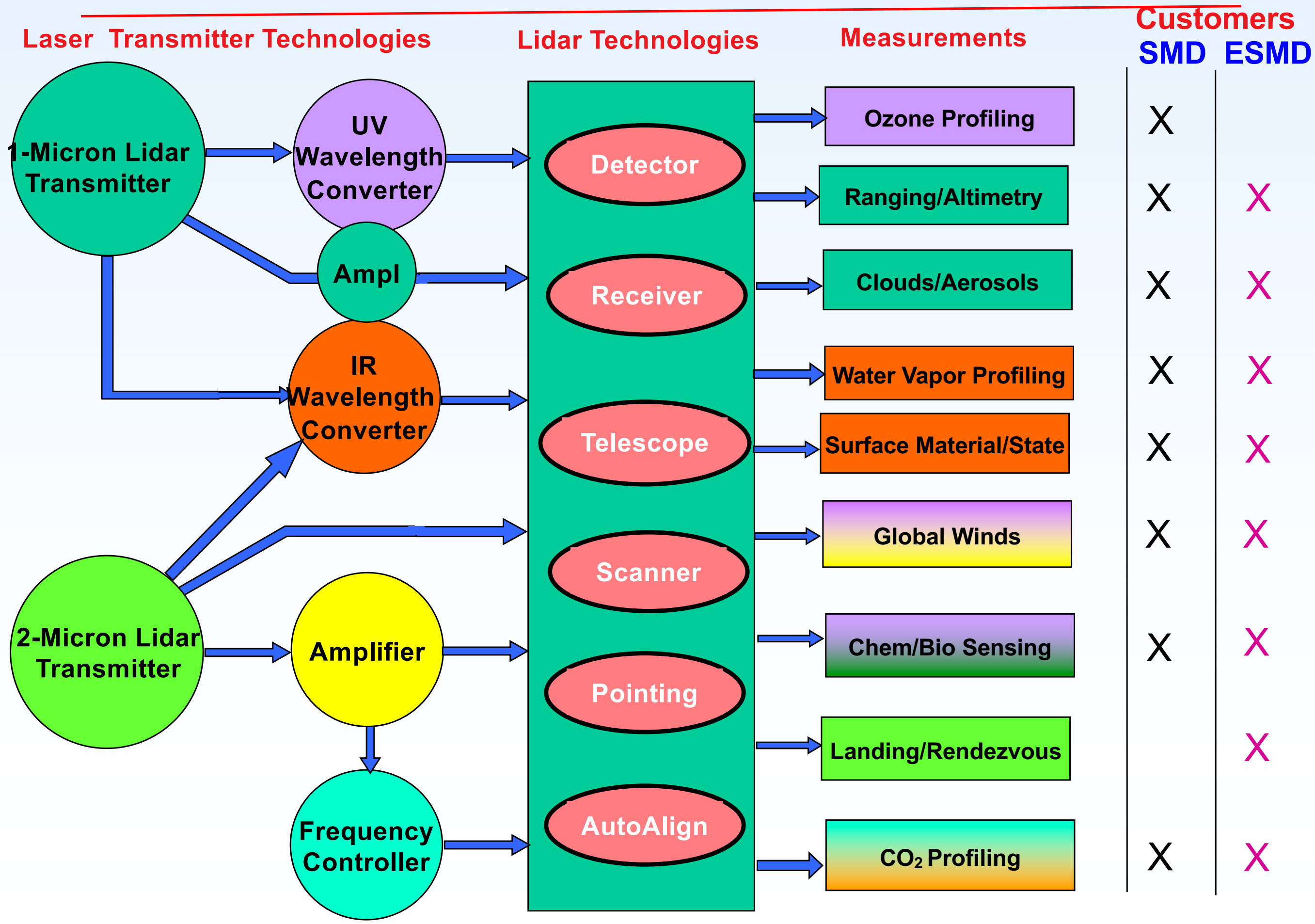
Exploration Systems

- *Lander Guidance/ Control*
- *Lander Hazardous Winds/Dust Avoidance*
- *Mars Atmospheric Winds*
- *Biological Elements (C, N, H, S, P)*
- *Optical Communication*
- *Spacecraft Automatic Rendezvous/Capture*
- *Wind Profiling for Launch Vehicles*

Aeronautics

- *Turbulence detection*
- *Wind shear detection*
- *Wake vortices*

Enabling Technology Elements



TIM on Active Optical Systems

- **Held on July 31 – Aug. 2, 2018**
- **Purpose (from Proceedings intro)**

  "The TIM aimed at focusing NASA's directions to attain the necessary TRLs to meet the Agency-level priority Active Optical measurements in Space and Aeronautics"

- **Covered active optical systems for Earth science; planetary science; entry, descent, and landing; aeronautics; and optical communication**
- **Proceedings available from NASA Technical Report server**
  - https://ntrs.nasa.gov/search.jsp
  - **Search for** 20200000065
  - **Includes assessment and recommendations, presentations, and written synopses of presentations**

Technical Report Cover Page

NASA/CP–2019-220422

Proceedings of the NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs

Edited by

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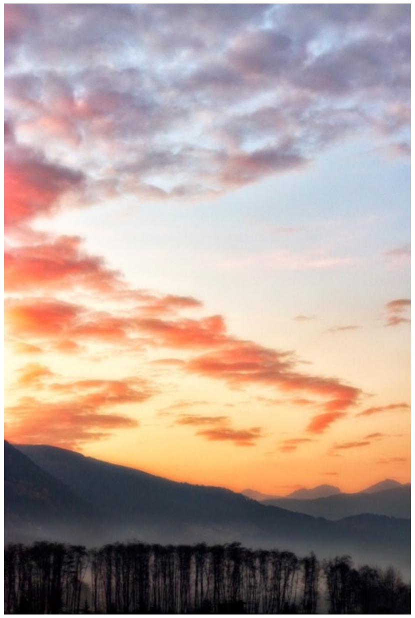
Langley Research Center, Hampton, Virginia

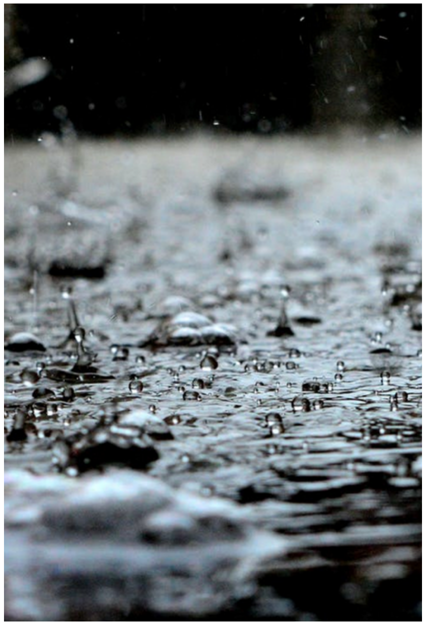
Water Vapor is a Key Atmospheric Constituent

Cloud Formation



Albedo

Precipitation

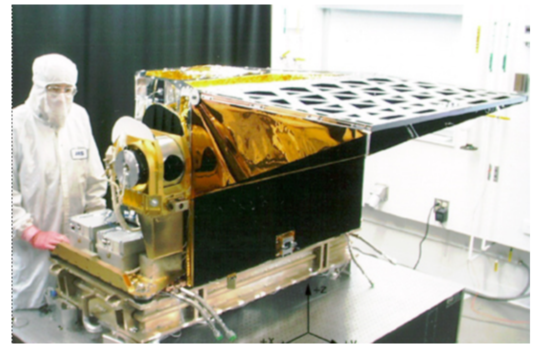


Water vapor plays a key role in weather, radiative balance, atmospheric dynamics, surface fluxes, and soil moisture – 2018 NAS decadal survey recognizes global, high-resolution measurements will revolutionize understanding

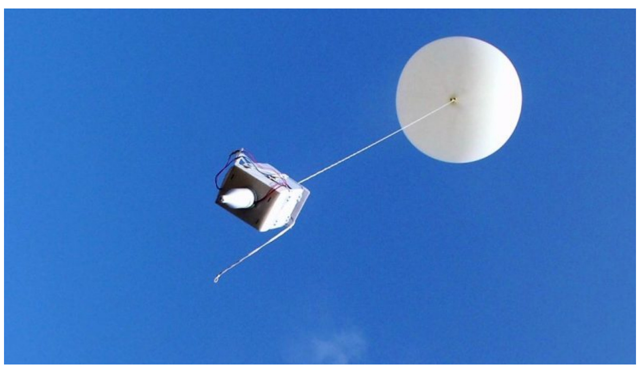
Water Vapor Measurements for Weather and Climate Prediction

Surface Measurements

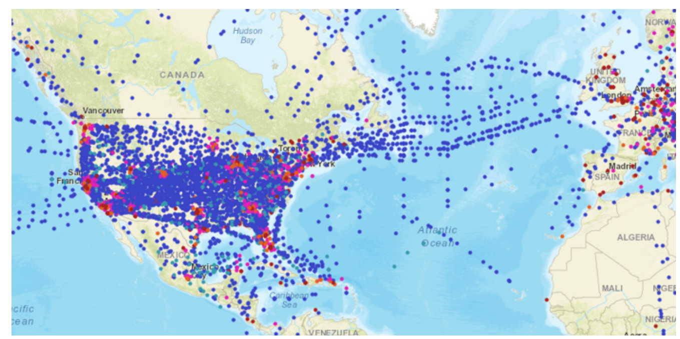
Satellite-based Passive Sounding



Radiosondes



Aircraft-Based Measurements



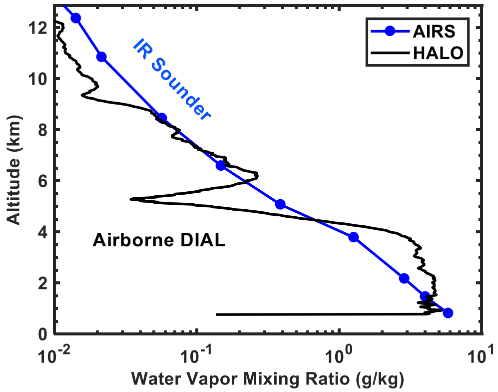
Water Vapor is a Key Atmospheric Constituent

- Passive IR and microwave sounders are the backbone of the numerical weather prediction and climate science communities
- They provide limited resolution and sensitivity in the lower troposphere (i. e., close to the Earth's surface)
- Water vapor was identified as being synergistic and cross-cutting over 5 of the 6 NASA Decadal Survey science and applications priorities
- Water vapor differential absorption lidar (DIAL) was identified as a potential candidate for accurate and high-resolution water vapor profiles

Space-based water-vapor lidar has been of interest for over three decades

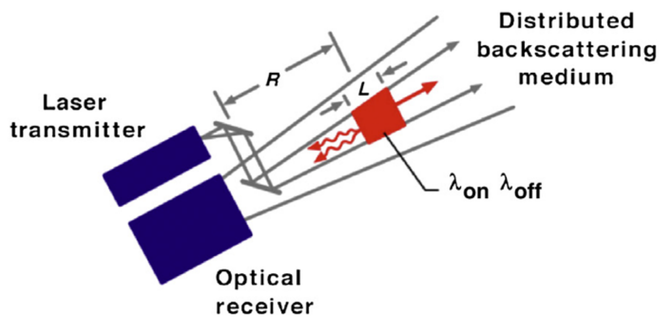
NAS 2018 Decadal Survey

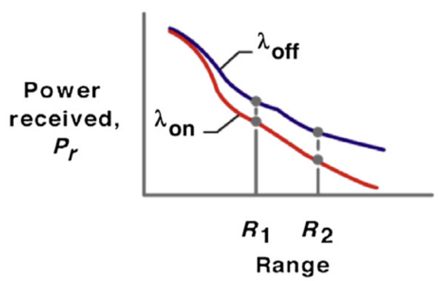
Water-Vapor Vertical Profile

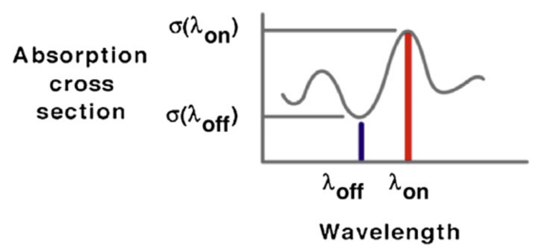


DIAL Concept

Ismail and Browell, in Encyclopedia of Atmospheric Sciences (2015)



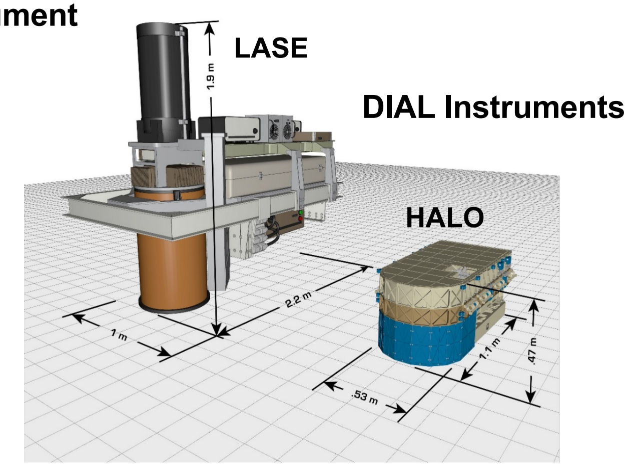


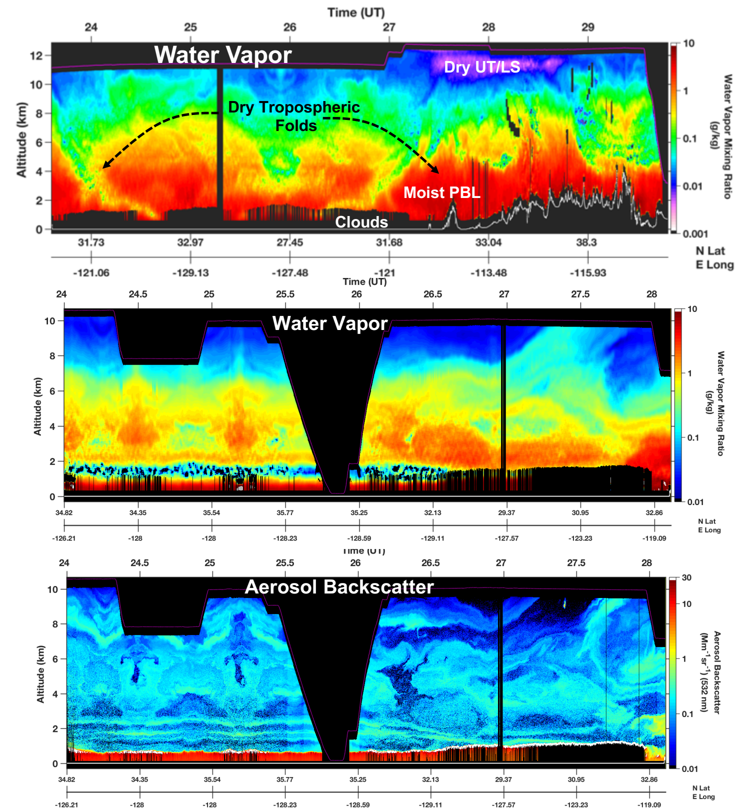


$$N_A = \frac{1}{2(R_2 - R_1)\,[\sigma_A(\lambda_{on}) - \sigma_A(\lambda_{off})]} \ln\left[\frac{P_{r_{on}}(R_1) \times P_{r_{off}}(R_2)}{P_{r_{off}}(R_1) \times P_{r_{on}}(R_2)}\right]$$

Airborne Water-Vapor DIAL

- NASA's Lidar Atmospheric Sensing Experiment (LASE) water vapor DIAL has been the community standard for high resolution measurements since the early 90s
- NASA LaRC has developed High Altitude Lidar Observatory (HALO), a replacement for LASE and serves as a testbed to vet technologies for future space-based missions
- Current laser transmitters are too inefficient and complex for space instrument



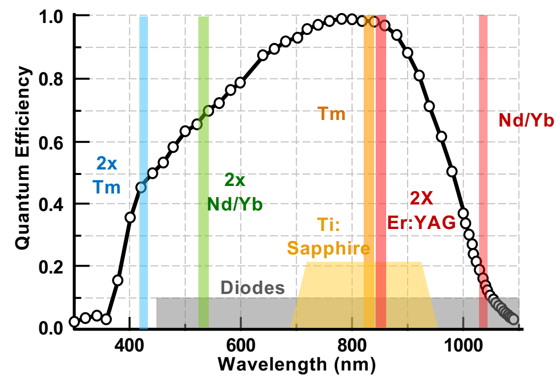


Lidar data courtesy of A. Nehrir (NASA LaRC)

Wavelength and Transmitter

- **Many water-vapor absorption bands – band around 820 nm is attractive for measurements**
  - Approximately right strength for needed measurement dynamic range
  - Efficient, low-noise Si detectors
- **Laser transmitter is the challenge**
  - High efficiency and low complexity for small SWaP
  - High power, good beam quality and pulsed operation

Silicon Sensitivity and Laser Wavelengths



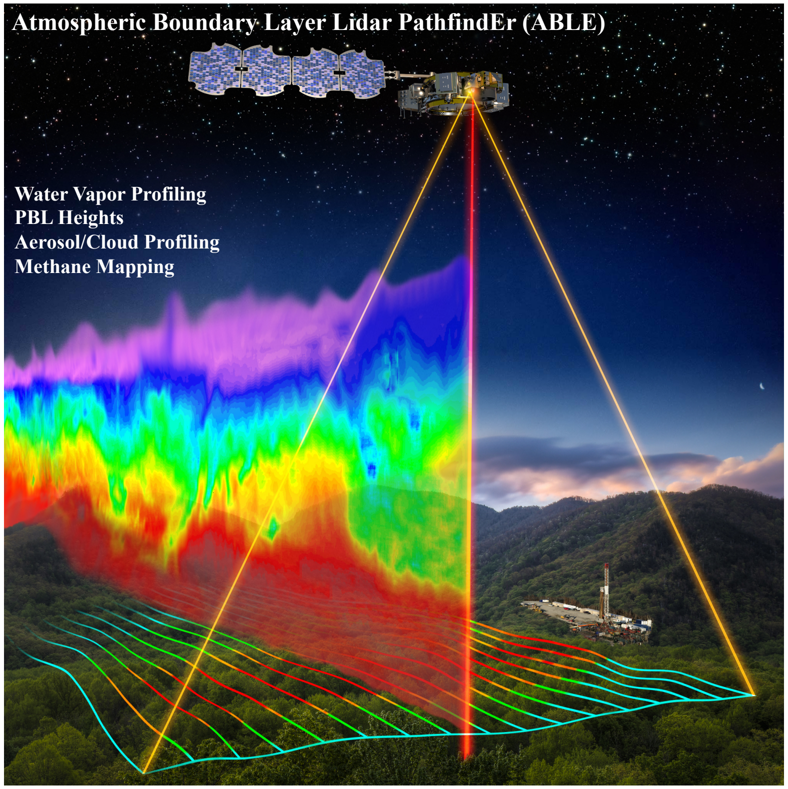
820 nm Laser Survey

	Laser	Efficiency	Power (W)	~Pulse Energy	Complexity	Schematic Setup
Existing	Ti:Sapphire	2%	5	mJ	4 parts	Diodes → Nd → 2x → Ti:Sapphire →
Existing	Diode	50%	1	µJ	1 part	Diodes
Potential	Tm:LiYF$_4$ (YLF)	8%	50	mJ	2 parts	Diodes → Tm:YLF →
Existing	Er:YAG	4%	3-10	mJ	3 parts	Diodes → Er:YAG → 2x →

A transmitter for space-based mission has been a challenge pursued for >3 decades

Small-Sat Water-Vapor Lidar

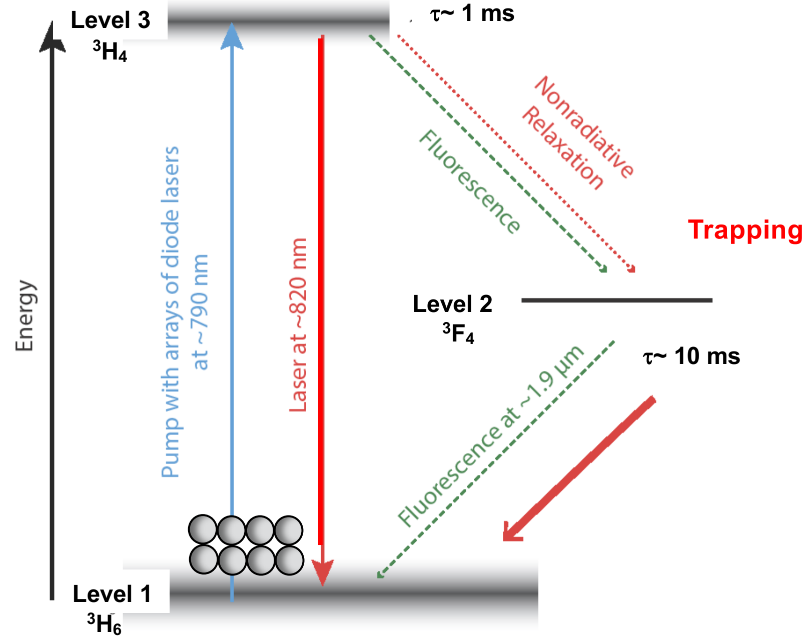
- **NASA LaRC is developing a small-sat (ESPA class) water vapor lidar concept with baseline of doubled Er:YAG transmitter**
- **Relies on photon-counting receivers and high pulse repetition frequency (PRF) transmitters**
  - **Nominal goals are 3-4 mJ/pulse at 2–3 kHz PRF**
  - **Increasing pulse energy to 10-15 mJ would greatly improve daytime performance**
- **Can Tm:YLF based transmitter provide relevant performance?**
  - **Potentially simpler and more efficient than Er:YAG**
  - **Er:YAG baseline demonstrated. Challenge is to scale peak and average power.**
  - **Tm:YLF development funded under NASA Advanced Components Technology (ACT) program**



Tm^{3+} Laser Physics and Materials

- Many reports on efficient 1.9-µm lasers
- Prior operation at ~820 nm largely limited to Tm-doped fluorzirconate fibers
- Intermediate states complicate dynamics because Tm ions trapped in long-lived Level 2
- Need to reduce Level 2 population
  - Cryogenic operation reduces needed Level 3 population for operation, which reduces Level 2 population
  - Choose host materials that have relatively large Level 3 lifetime
  - Reduce Level 2 population by lasing on Level 2 – Level 1 transition at 1.9 µm
- Physics in part validated by low-power demonstrations in Tm:YAG and Tm:YLF

Tm^{3+} Energy Levels



T. Y. Fan et. al., "Cryogenic Tm:YAG Laser in the Near Infrared," IEEE J. Quant. Electron., vol. 51, 10 (2015)
C. E. Aleshire et al., "Efficient cryogenic near-infrared Tm:YLF laser," Opt. Express 25, 13408-13413 (2017)

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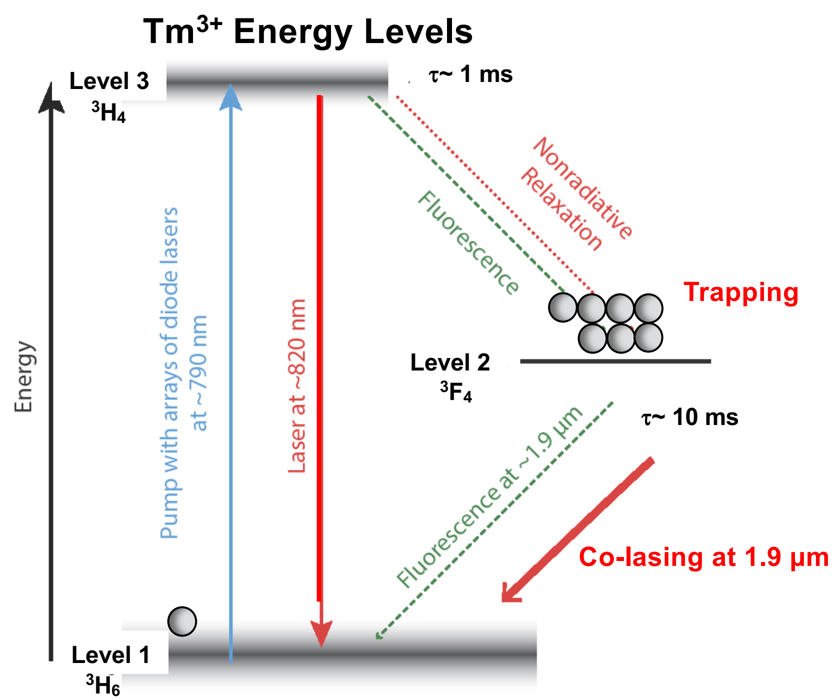

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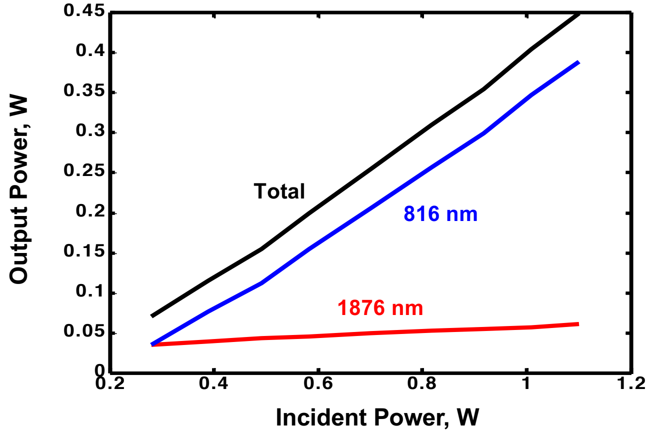
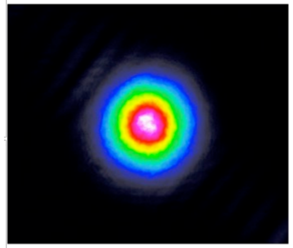
Tm:YLF CW Results using Liquid Nitrogen Cooling

- Laser resonator designed for simultaneous operation at 820 nm and 1.9 µm transitions
  – Force co-lasing to reduce population trapping
- CW slope efficiency is 46% (relative to incident power) using a Ti:S pump laser – approaching efficiency for Nd:YAG at 1.06 µm
- CW models predict output at 1.9 µm should be nearly constant with pump power, as observed
- Near-diffraction-limited output beam

Laser Performance



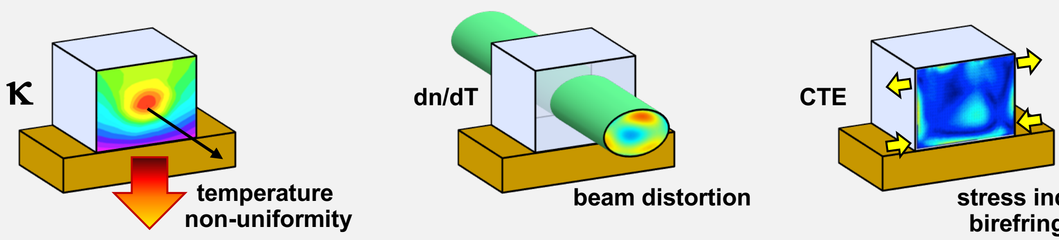
Output Beam



Results validate cw models and confirm effects due to population trapping

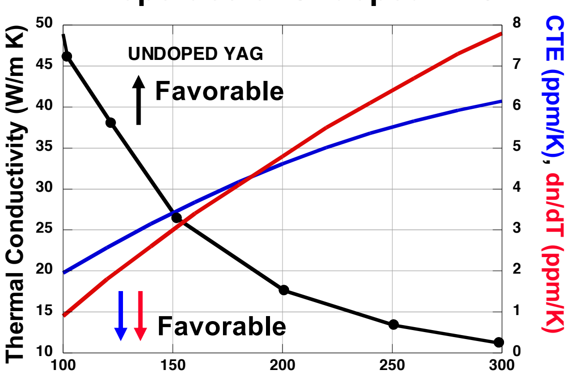
Thermo-optic Properties at Cryogenic Temperature

Thermal effects limit average power and beam quality



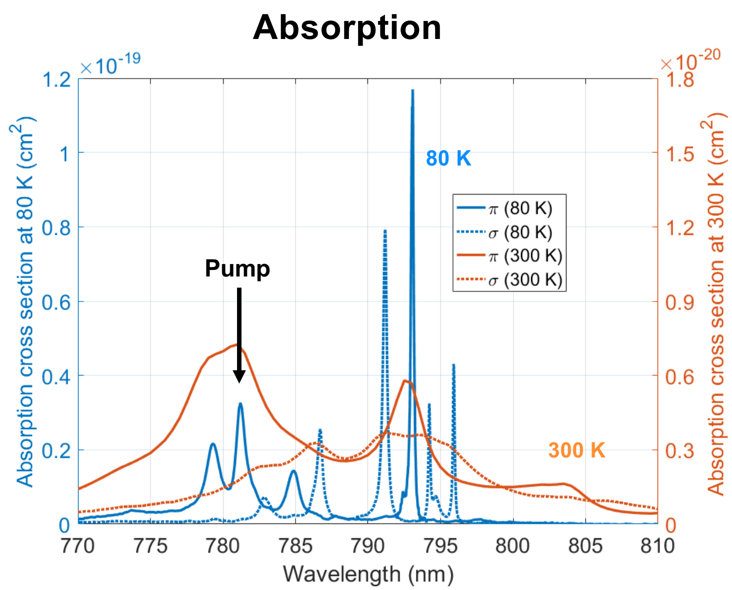
- **Poor thermal conductivity κ can inhibit heat removal, resulting in large temperature non-uniformity**
- **This changes the index, through dn/dT, and results in beam distortion**
- **Thermal expansion (CTE) creates stress which can cause depolarization and damage**

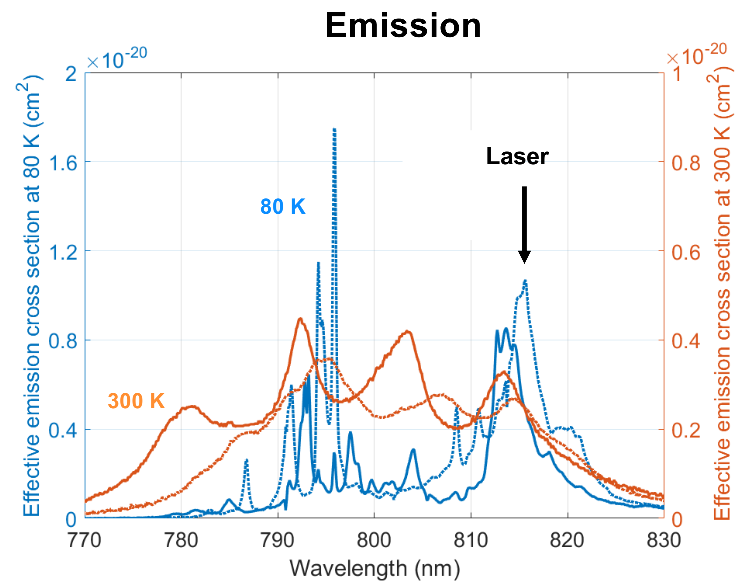
Properties of Undoped YAG



Cryogenic cooling significantly improves thermo-optic properties in crystalline dielectrics

Tm:YLF Spectra



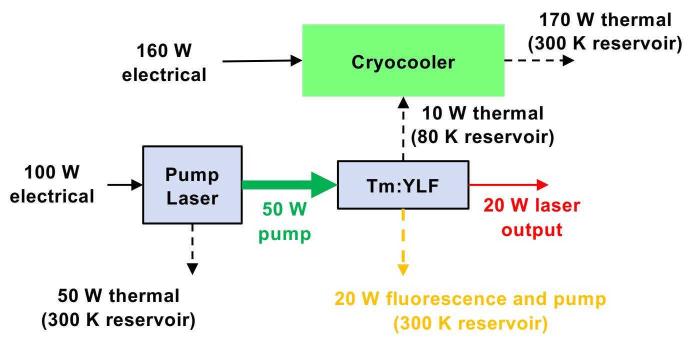


Absorption matches efficient diode laser pumps and emission matches water-vapor absorption lines in 812-817 nm range

Tm:YLF Lidar Transmitter Attributes

- Pulsed operation – few kHz pulse repetition frequency (PRF) with pulse width in the < 1 μs range (sets vertical resolution)
- Pulse-to-pulse wavelength agility to move on/off water vapor absorption line
- Narrow linewidth (~ <100 MHz) and high spectral purity compared with water-vapor absorption features
- Relatively simple and efficient (including power required for cryocooler)

Average Power Accounting



Notional Performance Goals

Attribute	Goal
Pulse Energy	>10 mJ
PRF	2–3 kHz
Wavelength agility	Switch between pulses
Spectral purity	>99.9%
Electrical efficiency	>5%

Key is to demonstrate temporal waveforms, average power, and efficiency to serve as existence proof

Cryogenic Cooling

Liquid Nitrogen Cryostat

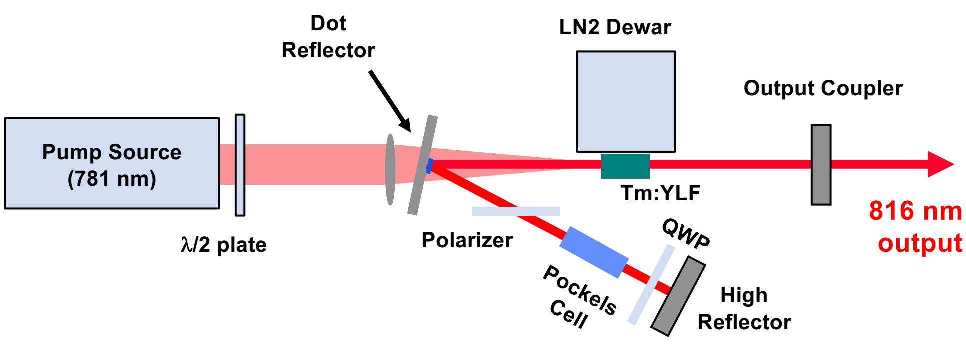
- **Pros**
  - Experimentally simple
  - Allows easy calorimetry by nitrogen boil-off rate
- **Cons**
  - Fixed temperature
  - LN2 consumable

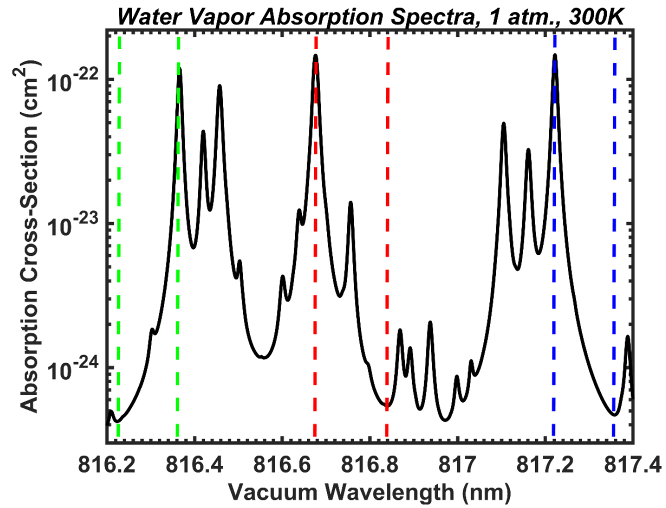
Stirling Cooler

- **Pros**
  - Only consumable is electricity
  - Allows easier temperature variation
- **Cons**
  - More challenging integration
  - Hard to do accurate calorimetry

Using LN2 cryostat for development but rely on Stirling cooler for space application

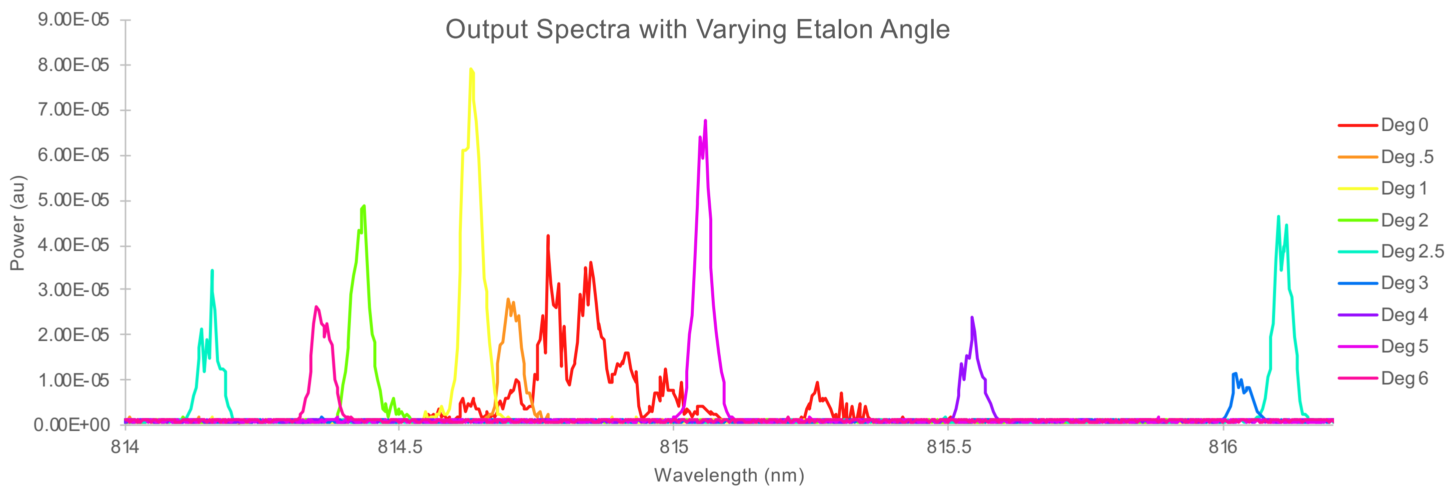
Laser Resonator Configuration





- **Standard resonator configuration for electro-optic Q-switching**

Tm:YLF Tuning Proof-of-Principle using an Etalon

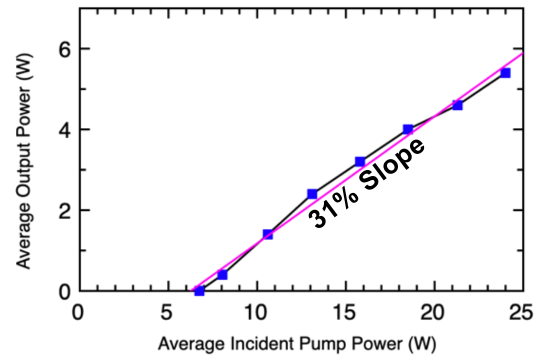


~2 nm of tuning demonstrated, limited by etalon thickness – shows ability to access multiple water-vapor absorption lines

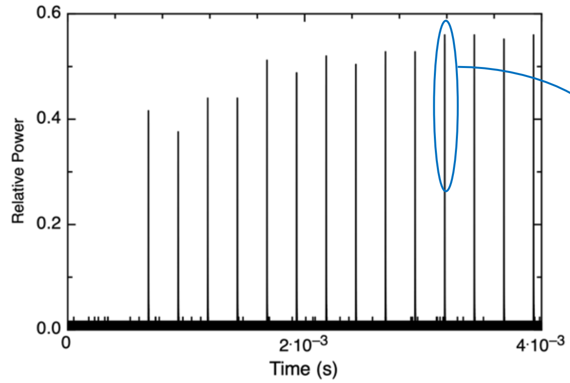
Q-Switched Operation at High PRF

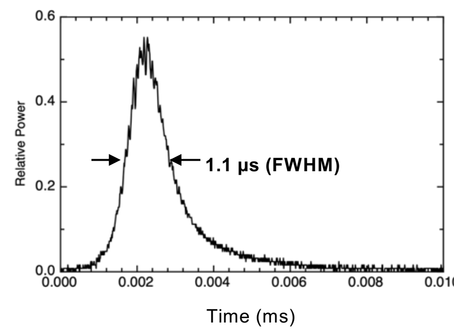
- **Burst mode operation (4 ms pump pulses at 50 Hz), net 20% pump duty cycle**
- **5.4 W average power with ~7.2 mJ/pulse (4 kHz Q-switched PRF, ~750 pulses per s)**
- **23% optical and 31% slope efficiency**
  - **Appears to be some rolling over at higher output**

Output Power



Tm:YLF Output Waveform for a Single Pump Pulse

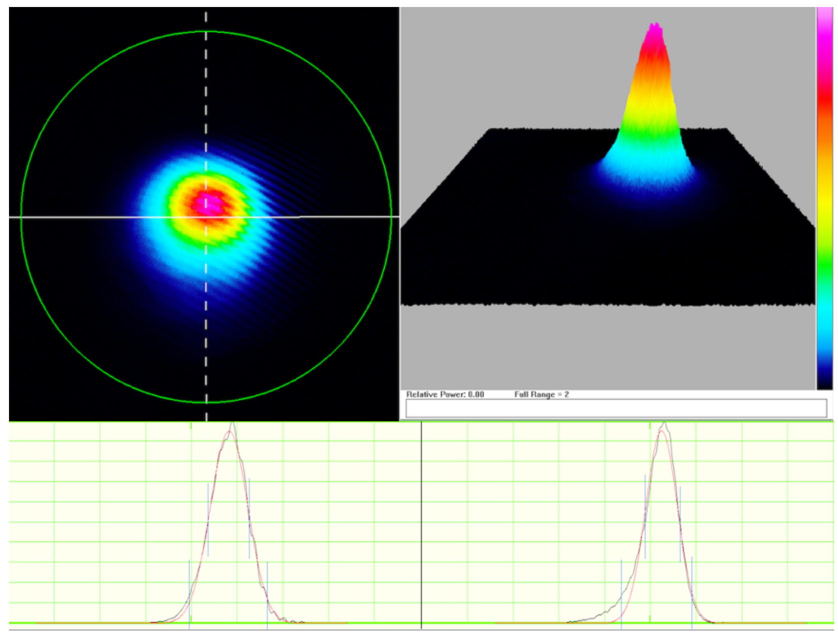




Beam Characteristics

- Beam is sampled in near field through HR mirror
  - Average output power is 5.8 W – maximum achieved in this demonstration
  - 4 ms pump pulses at 50 Hz
- Near TEM_{00}, Gaussian beam shape
- No evidence of thermo-optic effects – beam appears the same near threshold

Beam Image



Horizontal Vertical

Cryogenic operation enables excellent beam quality, as expected

Continuing Development

- **Improve efficiency and power**
  - Use lower doped Tm:YLF gain elements
  - Reduce intracavity losses – lower loss components and reduce water vapor inside resonator
- **Implement more lidar transmitter functionality**
  - Single-frequency operation
  - Stirling-cooler head implementation
  - Continuous 2 – 3 kHz PRF waveform
  - On-line, off-line operation with high spectral purity
- **Brassboard laser for use in airborne platform to increase TRL**
- **Other, non-transmitter challenges**
  - Single-photon detector arrays, particularly pushing photon detection efficiency
  - Narrowband filters, wavelength-agile filters of particular interest
- **Space-based measurements starting a decade from now?**

Results to date are promising but more needs to be done

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